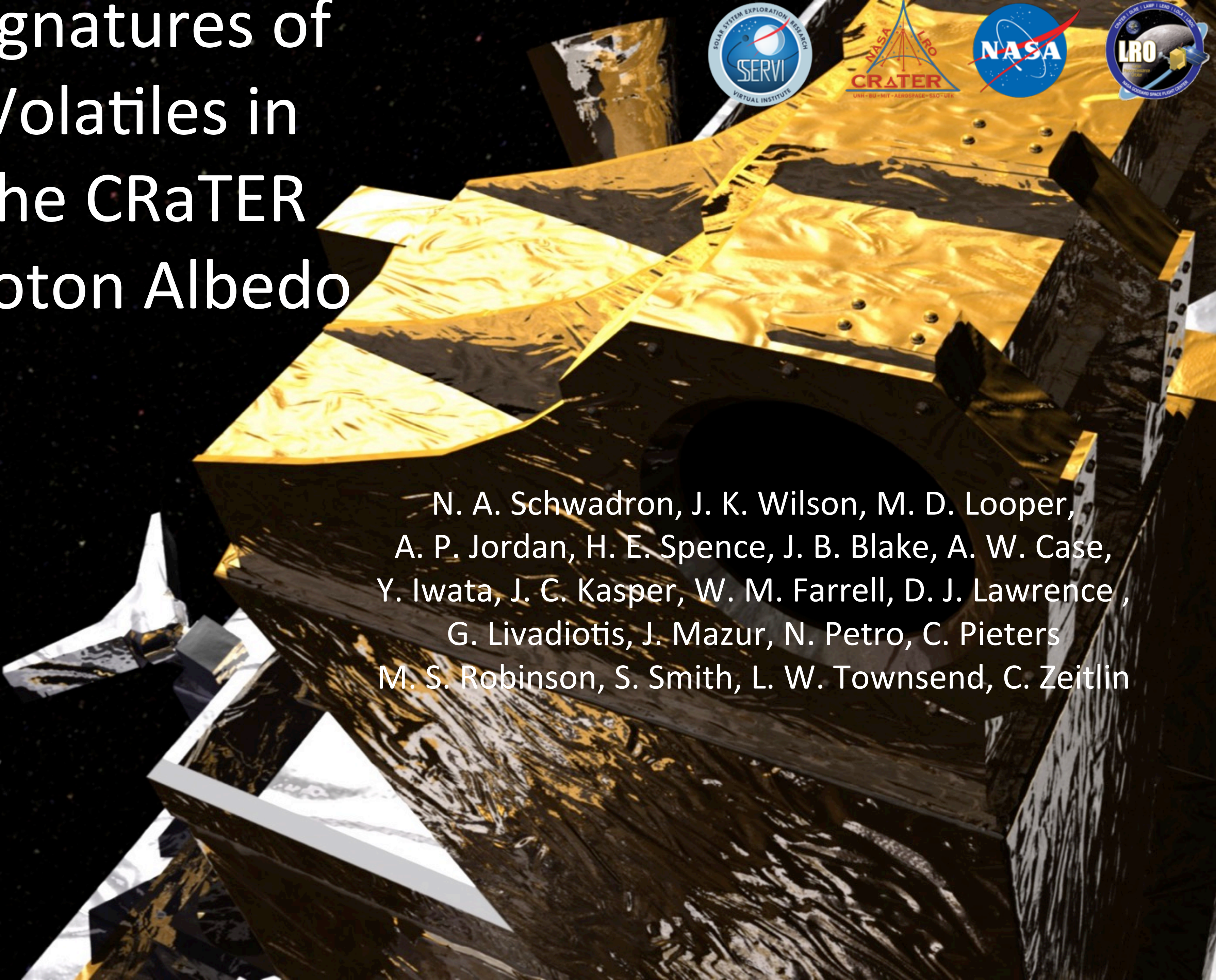
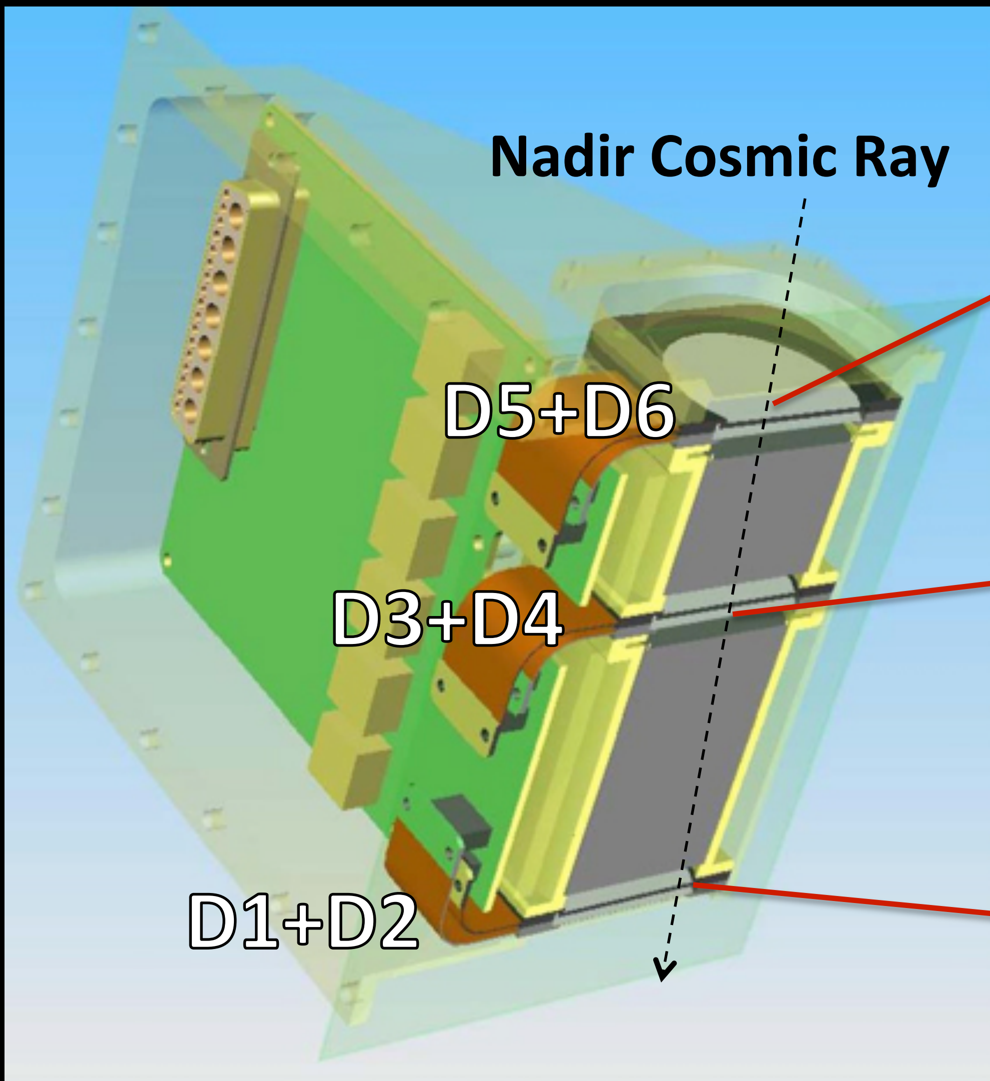
Signatures of Volatiles in the CRaTER Proton Albedo



N. A. Schwadron, J. K. Wilson, M. D. Looper,
A. P. Jordan, H. E. Spence, J. B. Blake, A. W. Case,
Y. Iwata, J. C. Kasper, W. M. Farrell, D. J. Lawrence ,
G. Livadiotis, J. Mazur, N. Petro, C. Pieters
M. S. Robinson, S. Smith, L. W. Townsend, C. Zeitlin

Kinetic Energy and Linear Energy Transfer (LET): Primary Data & Key to Directionality



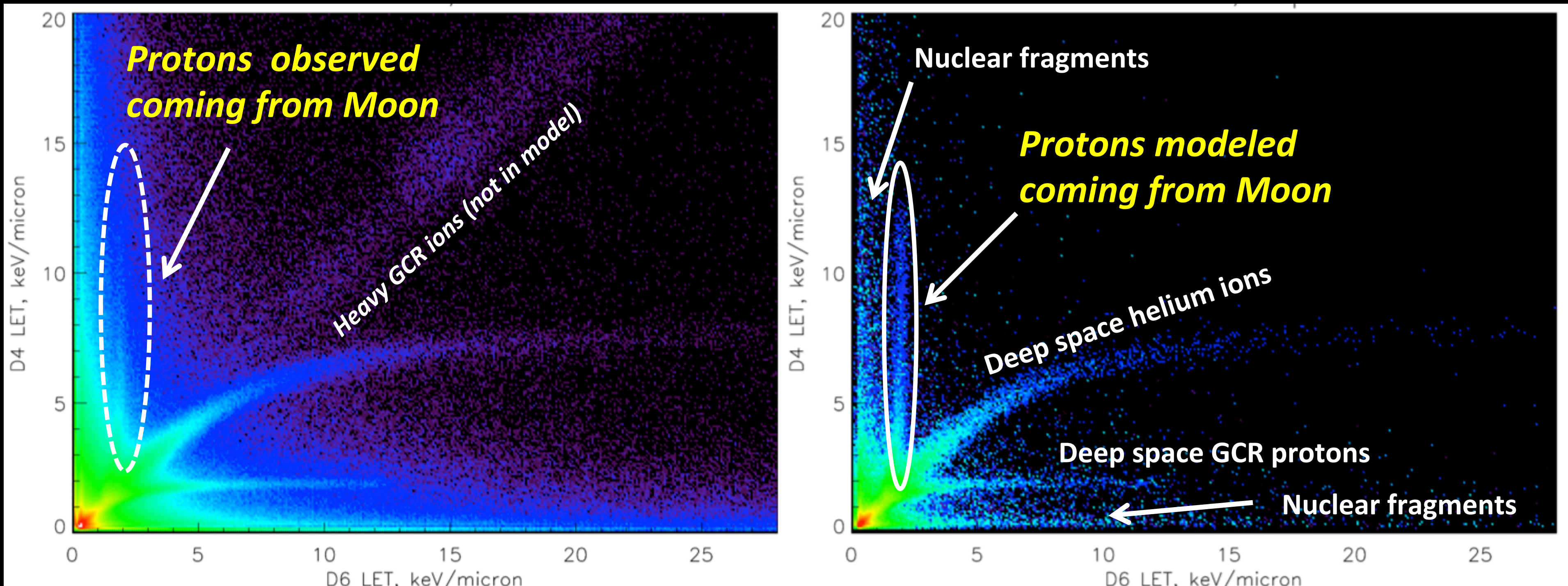
High Kinetic Energy
→ Low LET

Lower Kinetic Energy
→ Intermediate LET

Even lower Kinetic Energy
→ High LET

Proton Albedo and Nuclear "Scruff"

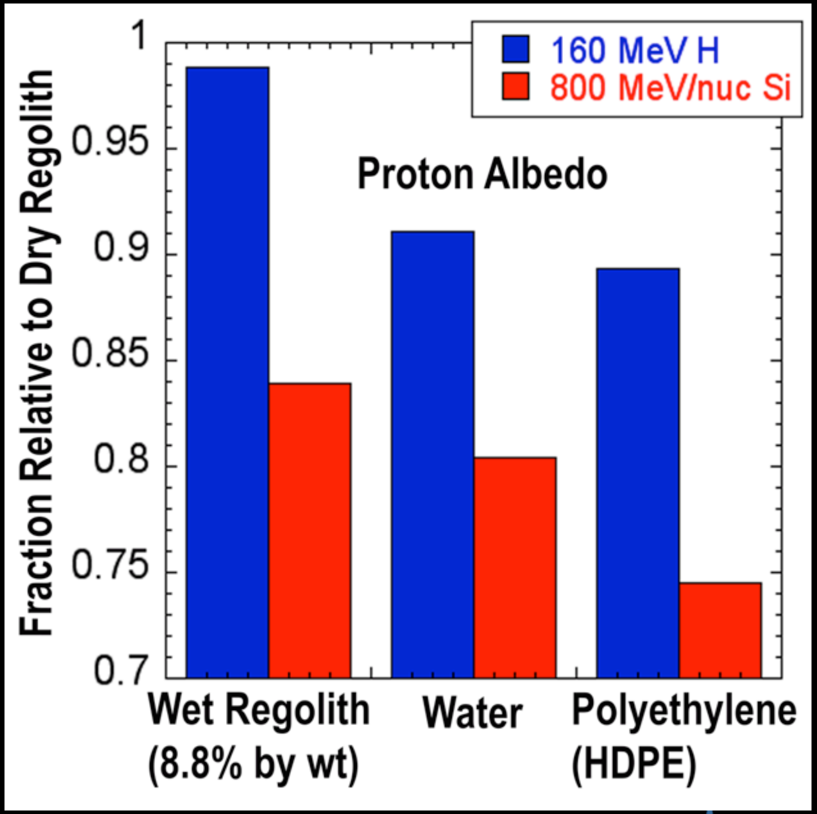
After Looper et al., 2013



4-Months of CRaTER Observations | **CRaTER Model Response to GCR**

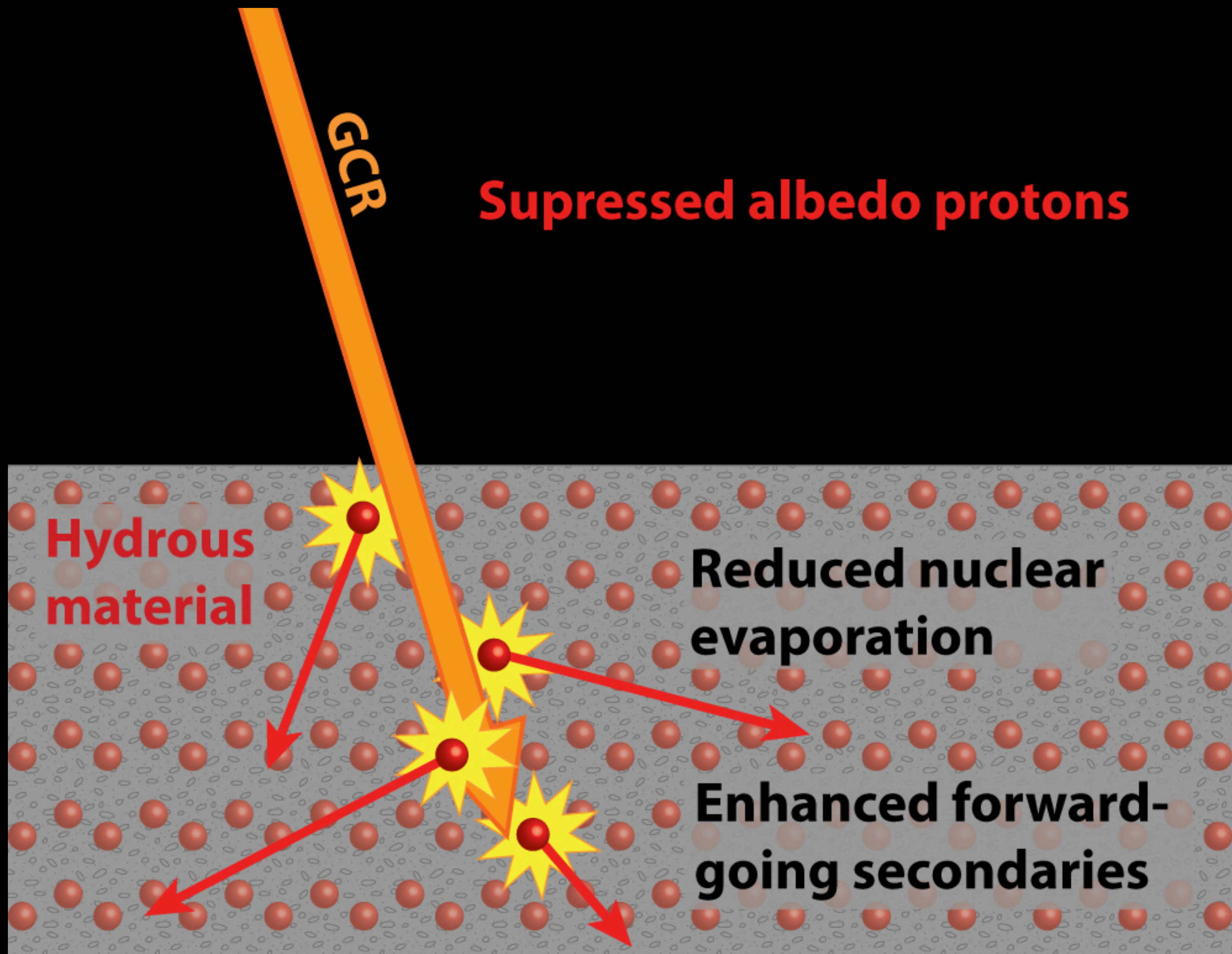
- **CRaTER confirms existence of lunar proton albedo (adds to well-known neutron albedo) → created by nuclear evaporation process**
- Upward-moving lunar protons (albedo) created from primary GCR slamming into the Moon
- Nuclear fragments (mostly pions, kaons, etc.) generated as GCR interacts with tissue-equivalent plastic within CRaTER – a major motivation for this experiment
- Heavy GCR ions (not included in model) seen clearly in observations out to Iron

Beam Measurements Show *Deficit* in Albedo from Wet Regolith



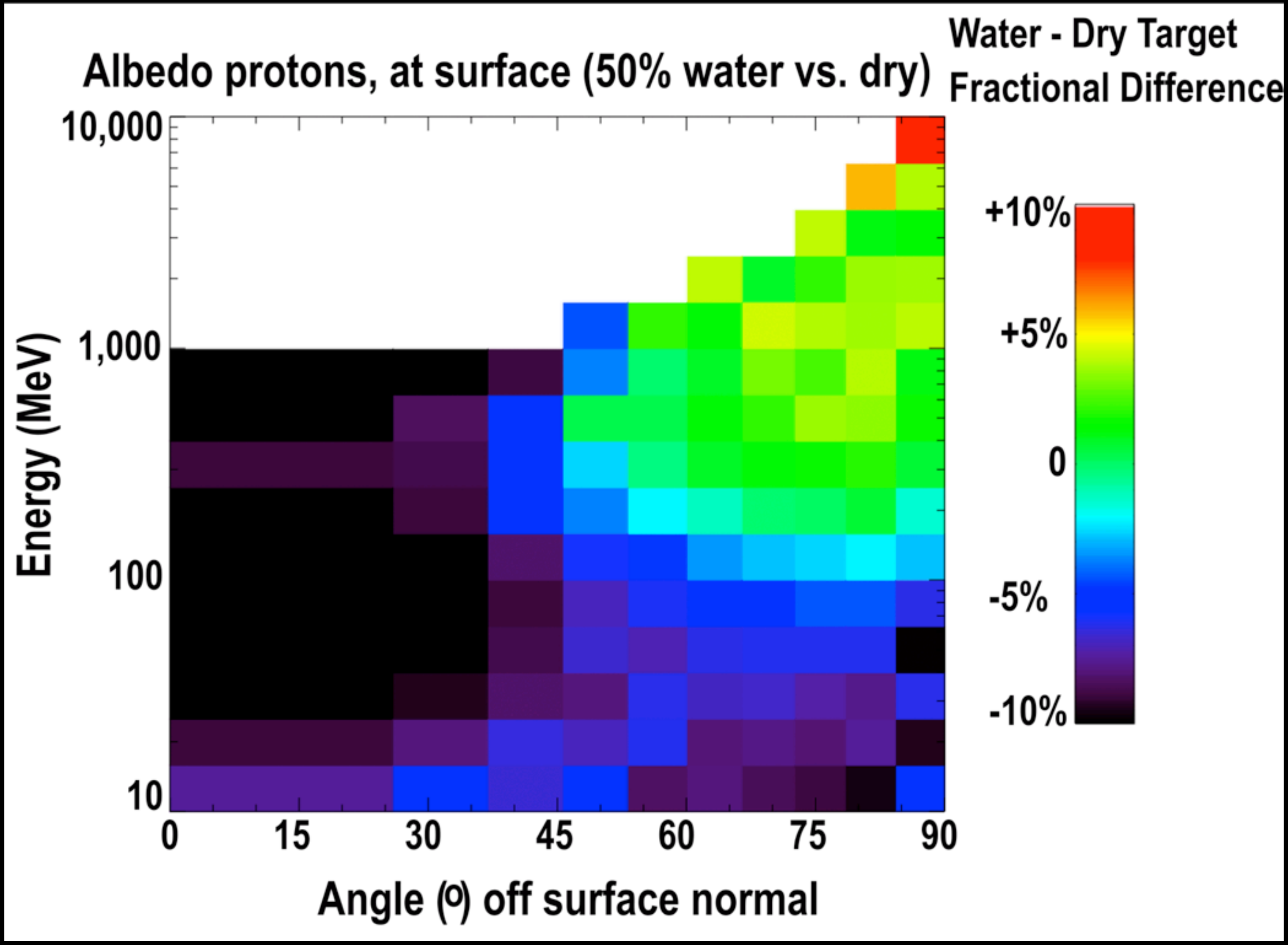
Schwadron et al., Icarus, 2015

Deficit Caused by Enhanced Forward Scattering



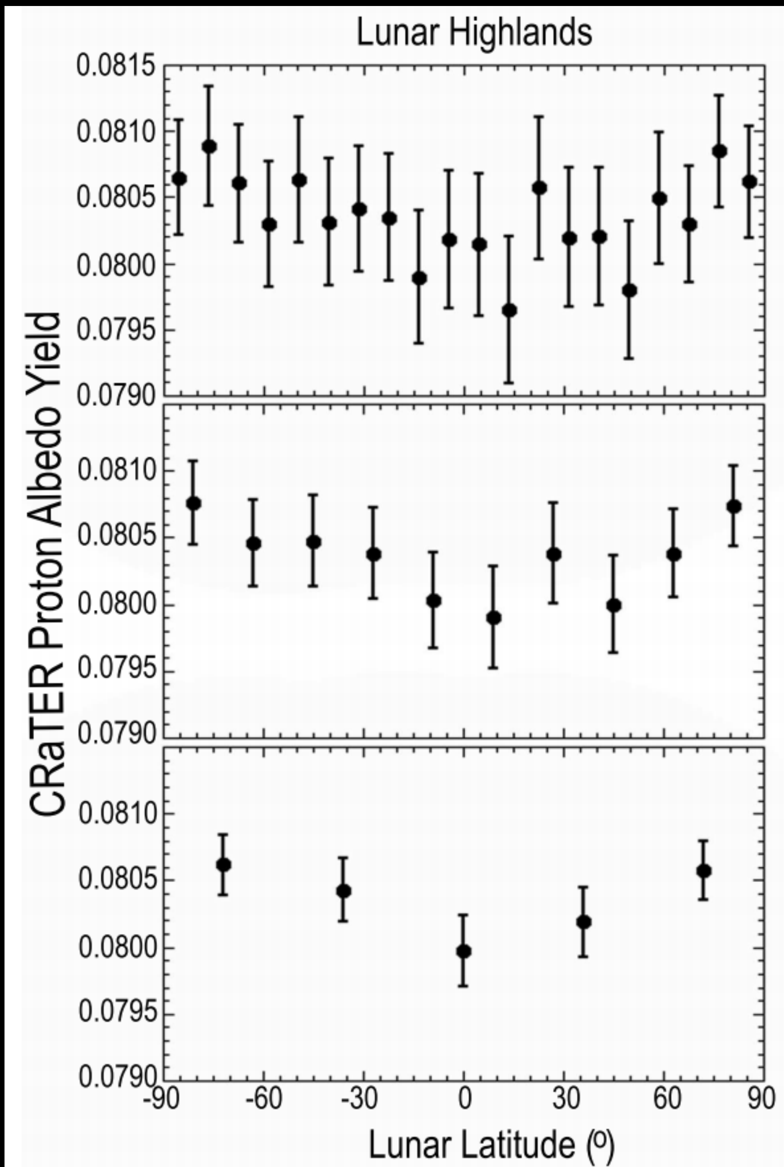
Schwadron et al., Icarus, 2015

Deficit in Albedo Confirmed from Geant4 SImulations

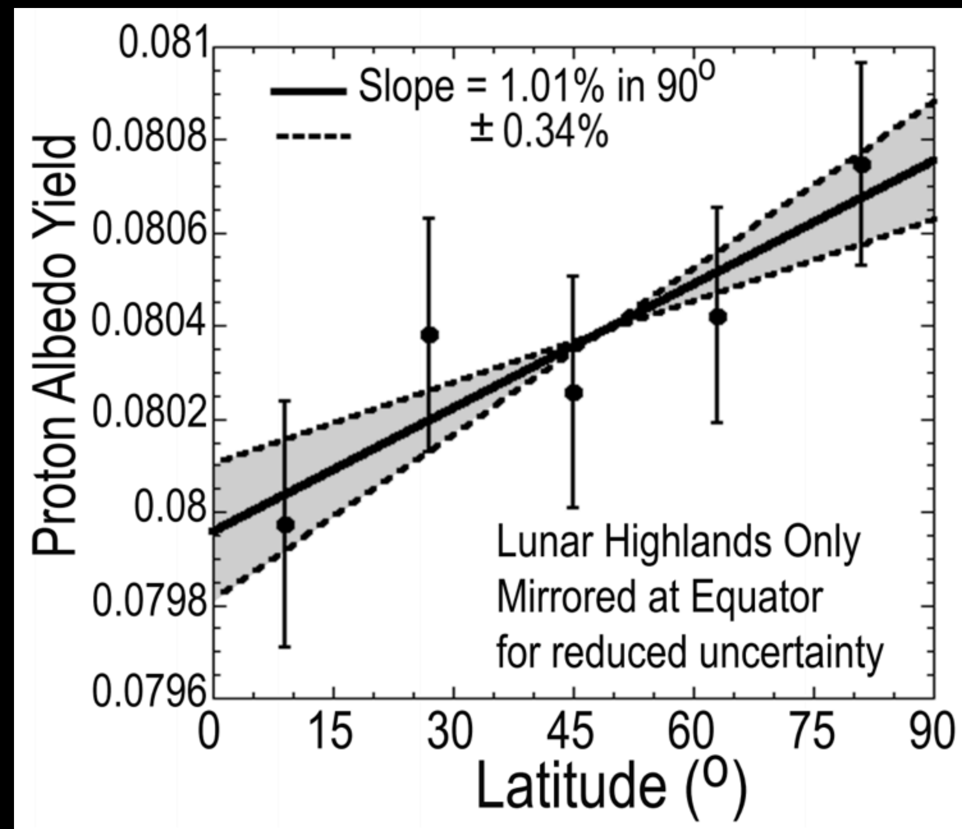


Schwadron et al., Icarus, 2015

Proton Albedo with Latitude in Highlands



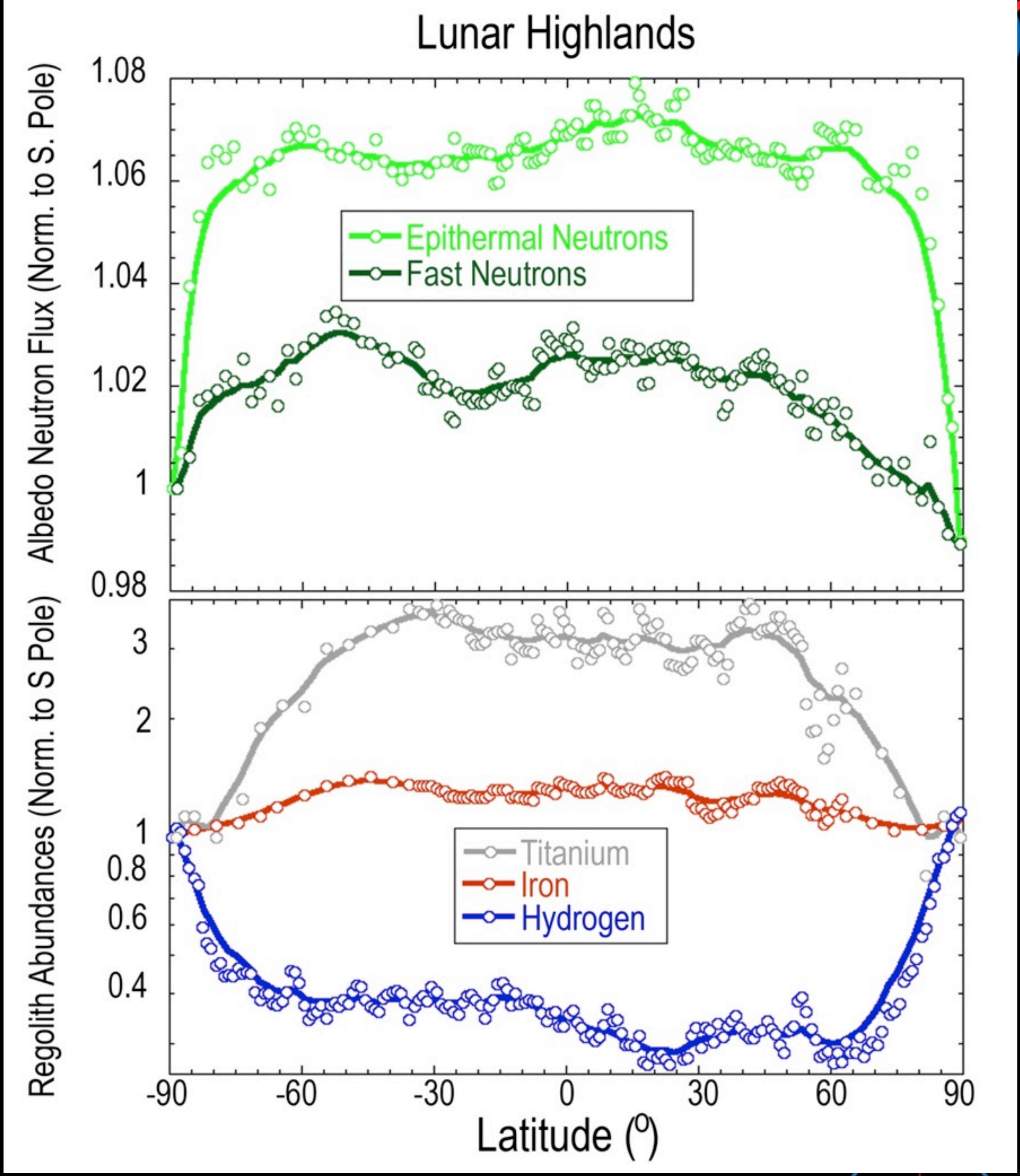
See Wilson et al. Poster – **LEAG, #2064**



Schwadron et al., Icarus, 2015

No clear links to other observations

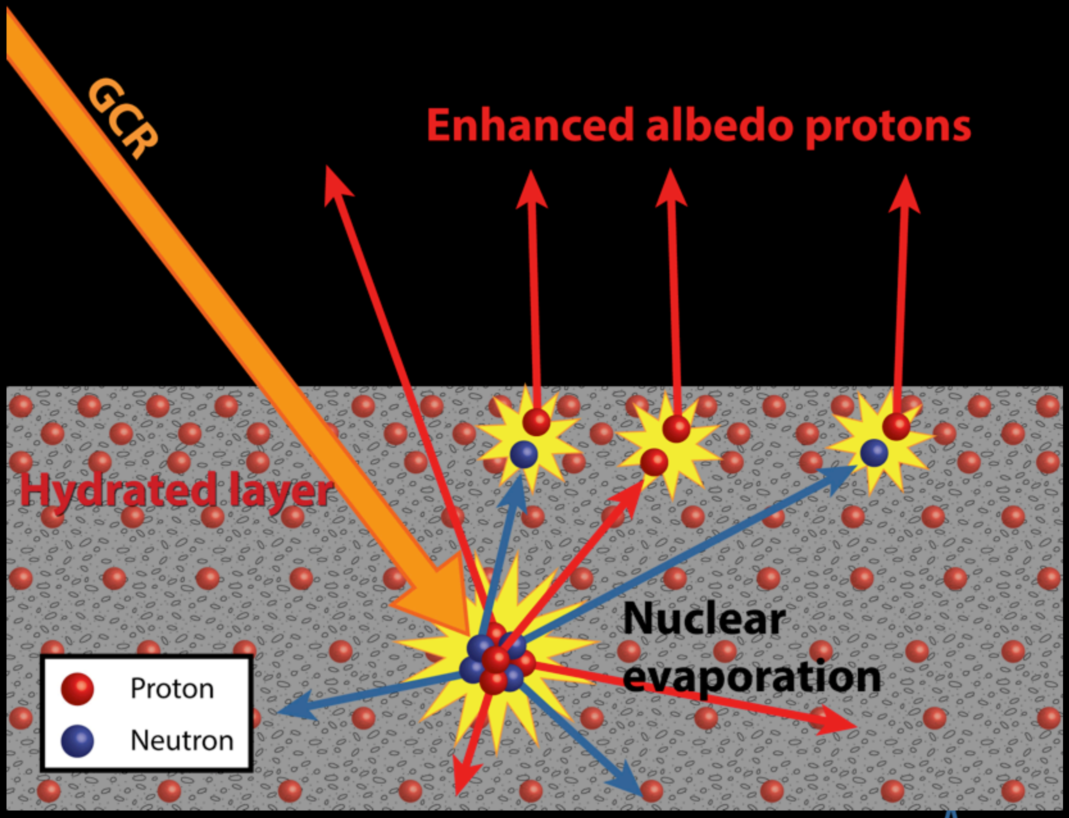
- *Positive Lat. Gradient* inconsistent with epithermal and fast neutrons
- Inconsistent with nuclear evaporation from heavies



Schwadron et al., Icarus, 2015

Idea: Production of Tertiary Protons

- Step 1: Production of collision products (lots of neutrons) through nuclear evaporation at depth
- Step 2: Knock-on collisions (p-n) create tertiary protons



Schwadron et al., Icarus, 2015

Hydrated Surface Layer - Properties

$$F_p' = F_p + F_n(dn_H \sigma_{np})$$

F_p' Proton Flux from Top regolith

F_p Proton Flux from depth

F_n Neutron Flux from depth

$$\Delta \approx (dn_H \sigma_{np}) F_n / F_p$$

Fractional Excess

$$dn_H \approx \Delta F_p / (F_n \sigma_{np})$$

Column density in upper layer

$$\Delta \ = \ 1.01 \pm 0.34\%$$

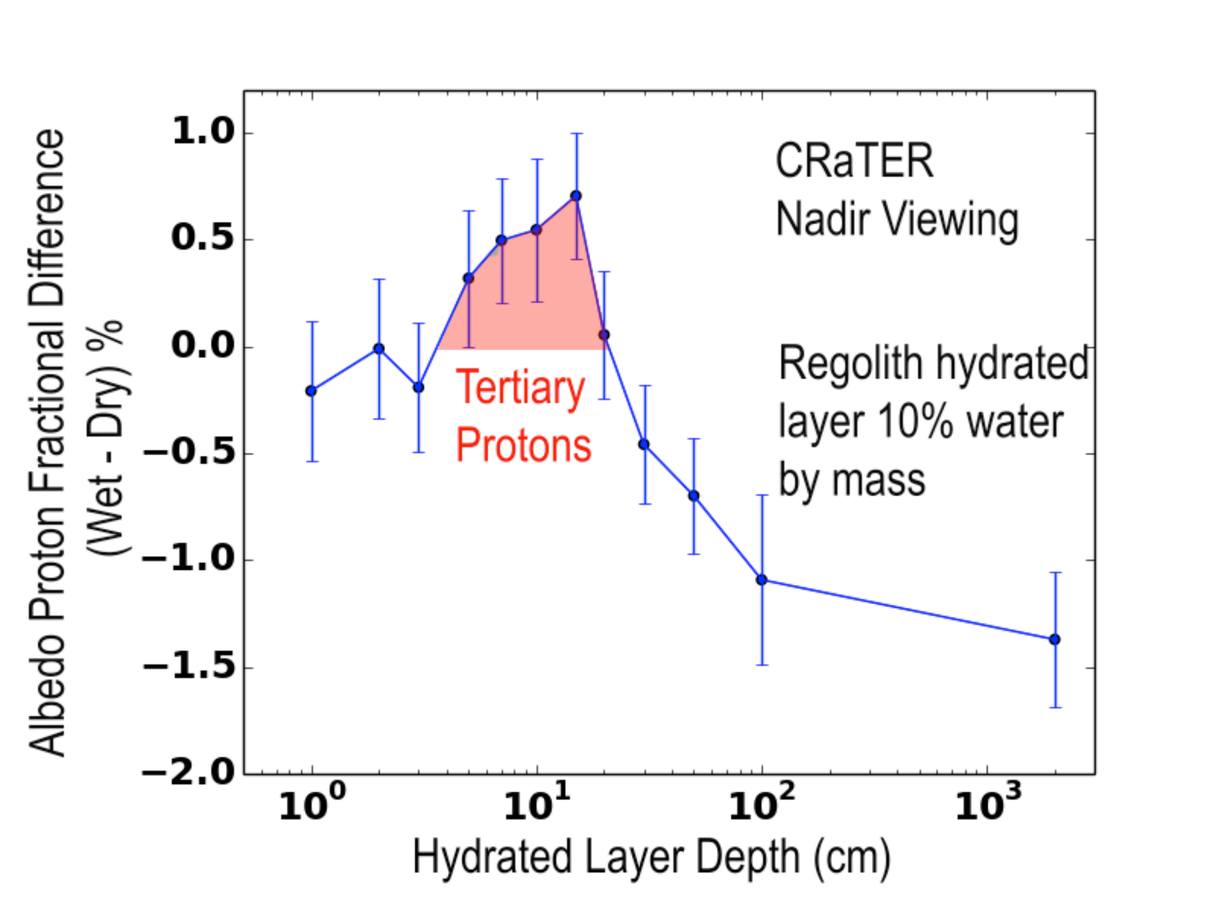
d ~ 20 cm → H 200 ppm by weight

d ~ 2 cm → H 2000 ppm by weight

Modeled H in cold traps 200-4000 ppm, Teodoro et al., GRL, 37, L12201, 2010

Geant 4 Simulations – Proof of Concept

- Simulations include *only* GCR proton input
- Sets a *minimum* for tertiary proton production!

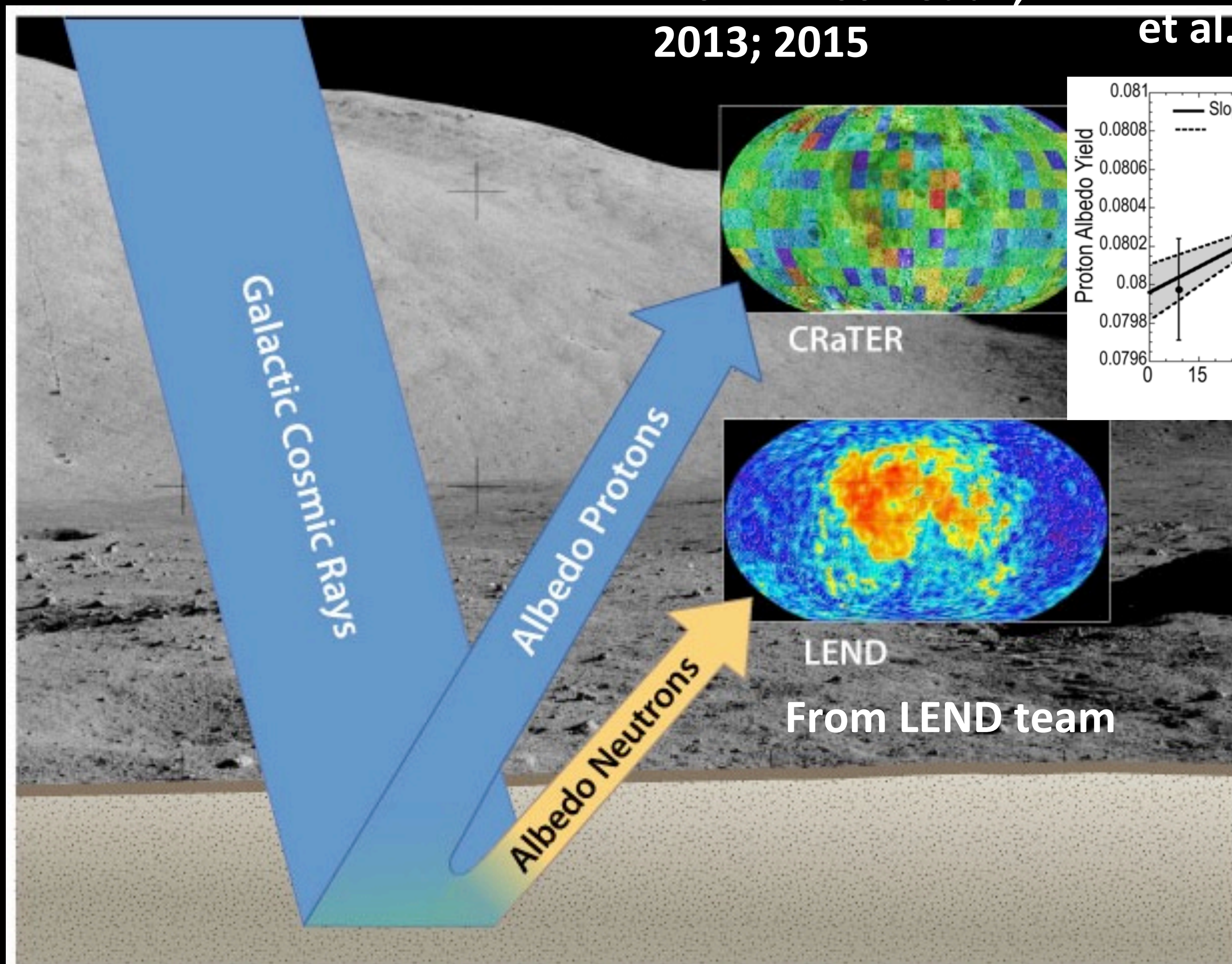


Schwadron et al., Icarus, 2015

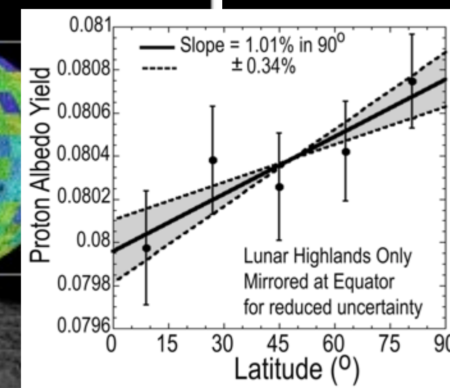
Remote sensing of regolith from GCR- produced energetic particle albedo

From Wilson et al., 2013; 2015

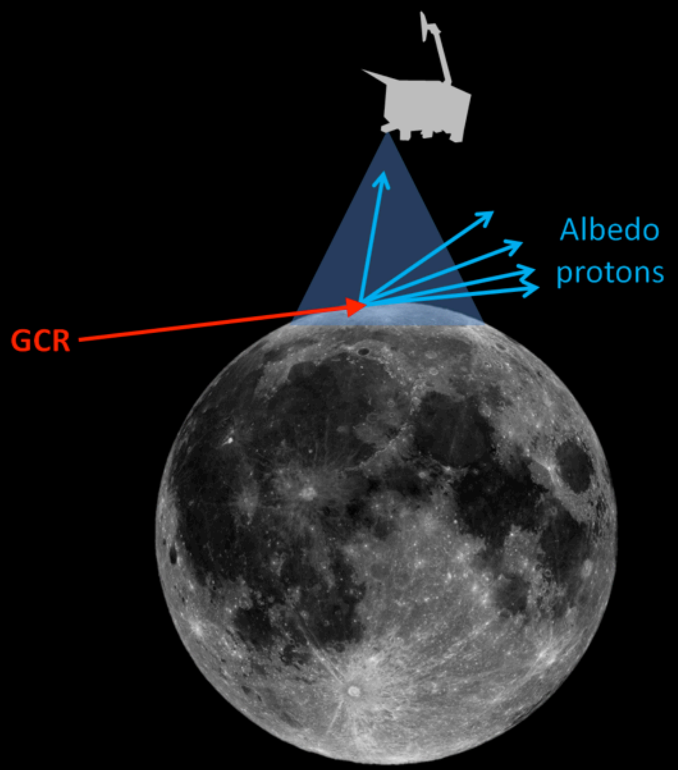
From Schwadron et al. 2015



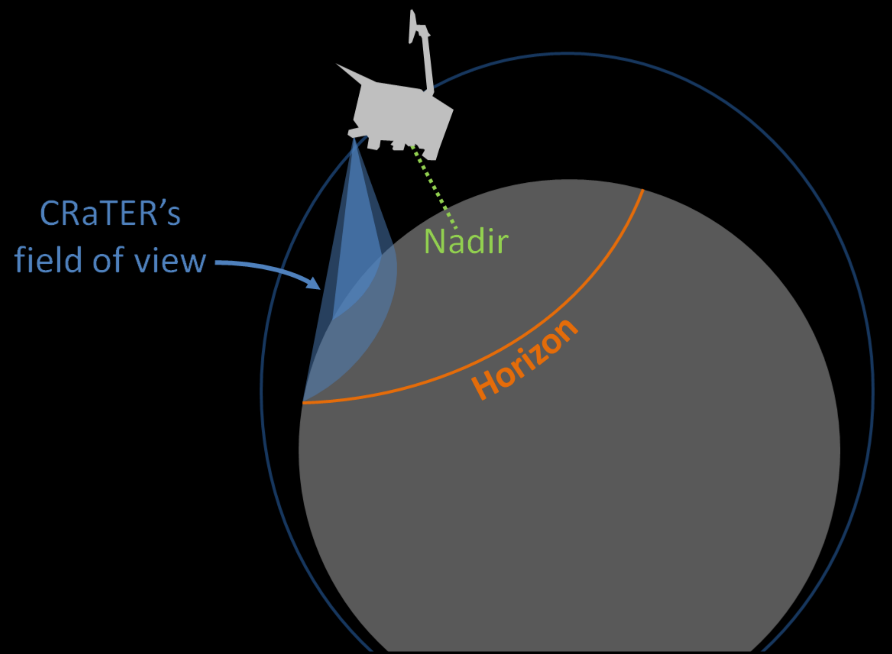
From LEND team



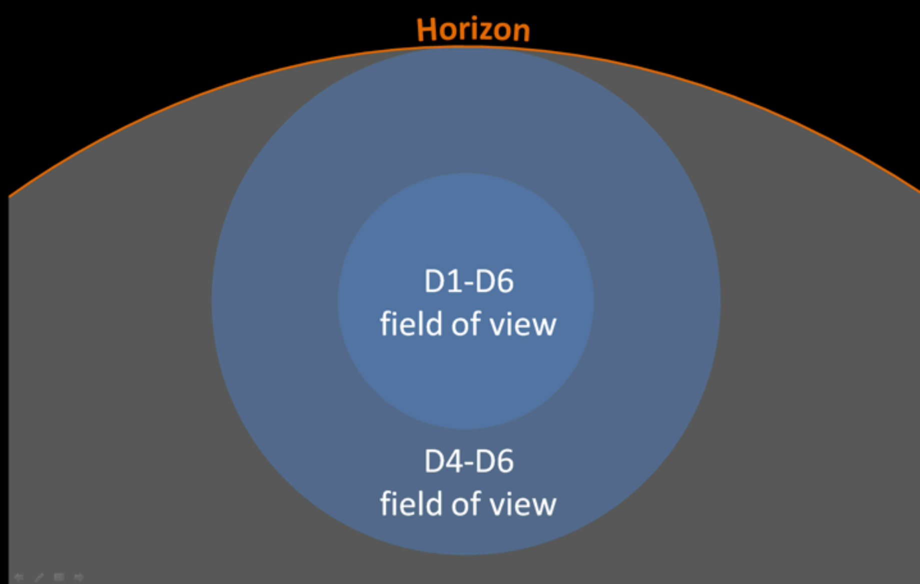
CRaTER Slews Importance for Extended Missions



View from the Sun



View from CRaTER

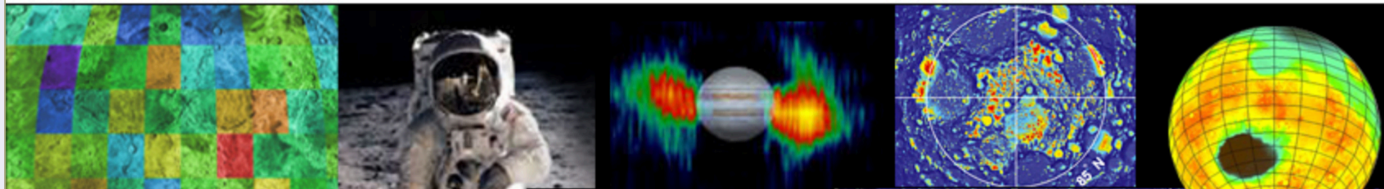


Summary

- LRO/CRaTER team highly productive, more than 50 papers on Planetary and Exploration Topics!
  - Highlighted in New ISSI Team on Radiation Interactions
- Discovery of Positive Latitude Gradient in Albedo Protons
  - Implications for Tertiary Proton Production
  - Possibly Produced from Upper 10 cm Hydrated Layer
- New CRaTER Observing Slews Allow New Tests (e.g., Time-of-Day Tests) in Next Phase of LRO!

INTERNATIONAL SPACE SCIENCE INSTITUTE

ISSI Research Team:
Radiation Interactions at Planetary Bodies



Abstract and Team Proposal | Team Members | Schedule & Meetings | Project Publications & Reports

The Internatioinal Space Science Institute (ISSI) is an Institute of Advanced Study, bringing together scientists from all over the world meet in a multi- and interdisciplinary setting to advance the understanding of results from space missions, ground based observations and laboratory experiments.

The international research teams are set up in response to an Annual Call by ISSI. Their goal is to carry out a resarch project leading to publications in scientific journals.

Proposal Abstract

Radiation Interactions at Planetary Bodies

SINCE THE LAUNCH of the Lunar Reconnaissance Orbiter (LRO) in 2009, the Comic Ray Telescope for the Effects of Radiation (CRaTER) has directly measured the Lunar radiation environment and mapped albedo protons (~100 MeV) coming from the Moon. Particle radiation has widespread effects on the lunar regolith ranging from chemical alteration of lunar volatiles to the formation of subsurface electric fields with the potential to cause dielectric breakdown that could modify the regolith in permanently shaded craters. LRO/CRaTER's direct measurements are transforming our understanding of the lunar radiation environment and its effects on the moon.

Similarly, the Radiation Assessment Detector (RAD) has been measuring the energetic particle radiation environment on the surface of Mars since the landing of the Curiosity rover in August 2012. The Martialn surface is protected by the atmosphere above; though only about 1% as thick as Earth's, its depth is sufficient to stop solar wind ions and the large majority of Solar Energetic Particles. RAD, like CRaTER, measures radiation dose, dose equivalent (related to human health risks), and particle spectra to enable rigorous tests of environment and transport models.

Recent measurements of galactic cosmic radiation and solar energetic particle radiation at other planetary objects (e.g., the moons of Mars) raise new fundamental questions about how radiation interacts at planetary bodies and what its long term impacts are.

This ISSI team will advance the study of radiation interactions.
Read more... (proposal and abstract, pdf)

Select Recent Publications

>50 Refereed Publications from the CRaTER team

6 refereed publications in 2014

11 refereed publications so far in 2015

CRaTER Special Issue of *Space Weather* - 10 Articles on CRaTER Measurements and Implications

- Schwadron, N. A., S. Smith and H. E. Spence, The CRaTER Special Issue of Space Weather: Building the observational foundation to deduce biological effects of space radiation, *Space Weather, 11,* 47, doi:10.1002/20026, 2013
- Case, A.W., The Deep-space Galactic Cosmic Ray Lineal Energy Spectrum, 2013, Space Weather, doi:10.1002/swe.20051
- Looper, M.D. et al., The Radiation Environment Near the Lunar Surface: CRaTER Observations and Geant4 Simulations. Space Weather, Vol. 11, 142-152, doi:10.1002/swe.20034, 2013
- Joyce, C.J., et al., Validation of PREDICCS Using CRaTER/LRO Observations During Three Major Solar Events in 2012 using CRaTER and the EMMREM Model. Space Weather, Vol. 11, pp. 1-11, doi:10.1002/swe.20059, 2013
- Spence, H. E., et al., Relative contributions of galactic cosmic rays and lunar proton "albedo" to dose and dose rates near the Moon, Space Weather, 11, 643, 2013
- Porter, J. A., et al., Radiation environment at the Moon: Comparisons of transport code modeling and measurements from the CRaTER instrument, Space Weather, 12, 329, 2014
- Joyce, C. J., et al., Radiation modeling in the Earth and Mars atmospheres using LRO/CRaTER with the EMMREM Module, Space Weather, 12, 112, 2014
- Zeitlin, C.;et al. Measurements of Galactic Cosmic Ray Shielding with the CRaTER Instrument. Space Weather, Vol. 11, pp. 284-296, doi:10.1002/swe.20043, 2013
- Schwadron, N., Bancroft, C., Bloser, P., Legere, J., Ryan, J., Smith, S., Spence, H., Mazur, J., and Zeitlin, C., Dose spectra from energetic particles and neutrons, Space Weather, 11, 547, 2013
- Schwadron et al., Does the Worsening Galactic Cosmic Radiation Environment Preclude Future Manned Deep Space Exploration, *Space Weather,* 2014

Select Recent Publications

Articles on Charging of Regolith and Changing Space Environment

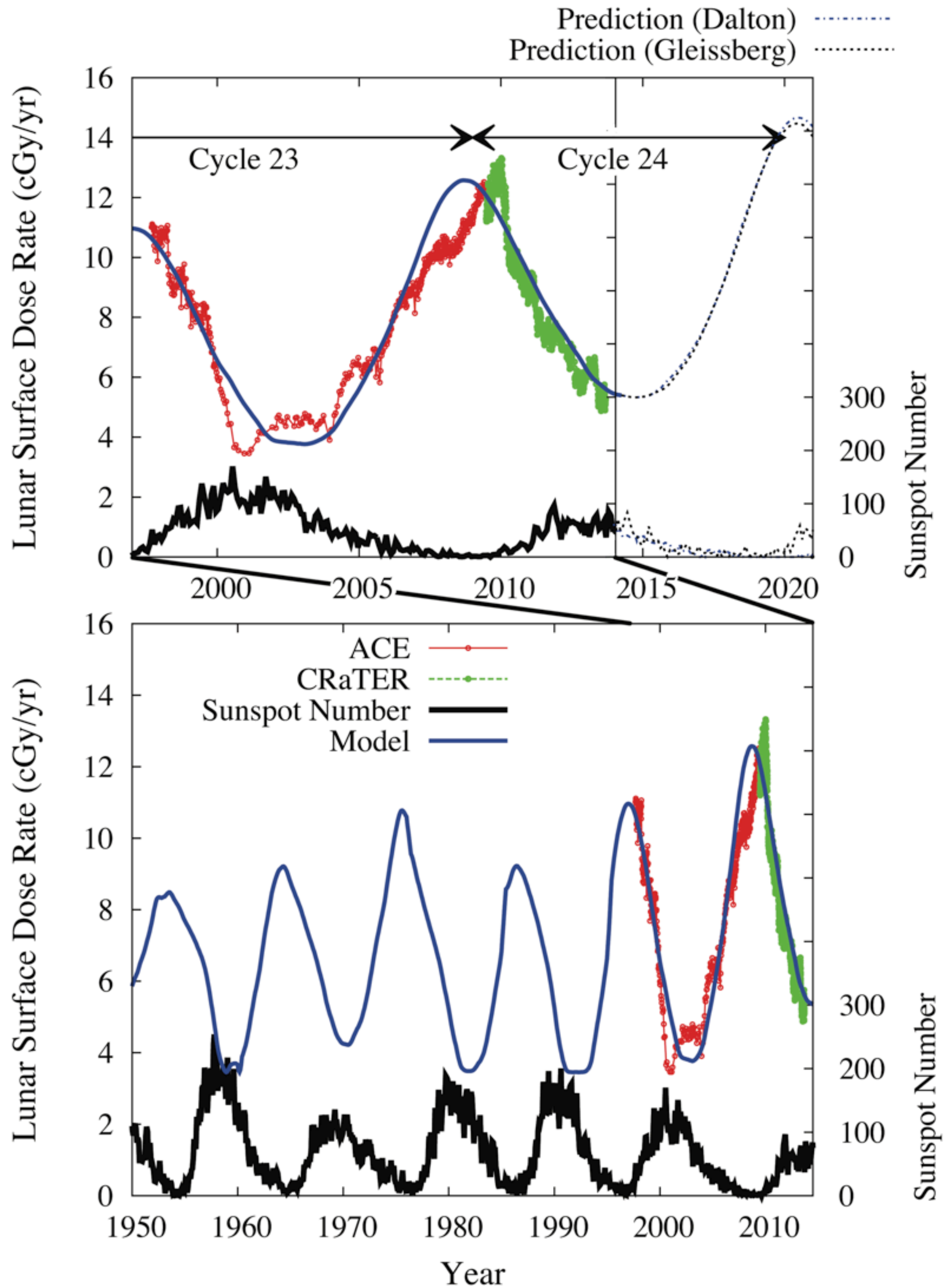
- Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A Schwadron, H. E. Spence and C. J. Joyce, **Deep dielectric charging of regolith withn the Moon's permanently shadowed regions**, JGR Planets, *119*, doi:10.1002/2014JE004648.
- Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A. Schwadron, and H. E. Spence (2015), Dielectric breakdown weathering of the Moon's polar regolith, *J. Geophys. Res. Planets,* in press, doi: 10.1002/2014JE004710.
- Smith, C. W., McCracken, K. G., Schwadron, N. A., and Goelzer, M. L., The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum, Space Weather, 12, 499, 2014
- Jordan et al.,The rate of dielectric breakdown weathering of lunar regolith in permanently shadowed regions, LRO Special Issue of Icarus, 2015
- Spence et al., Space Weathering throughout the solar system, in work, 2015

Articles on Proton Albedo and Implications

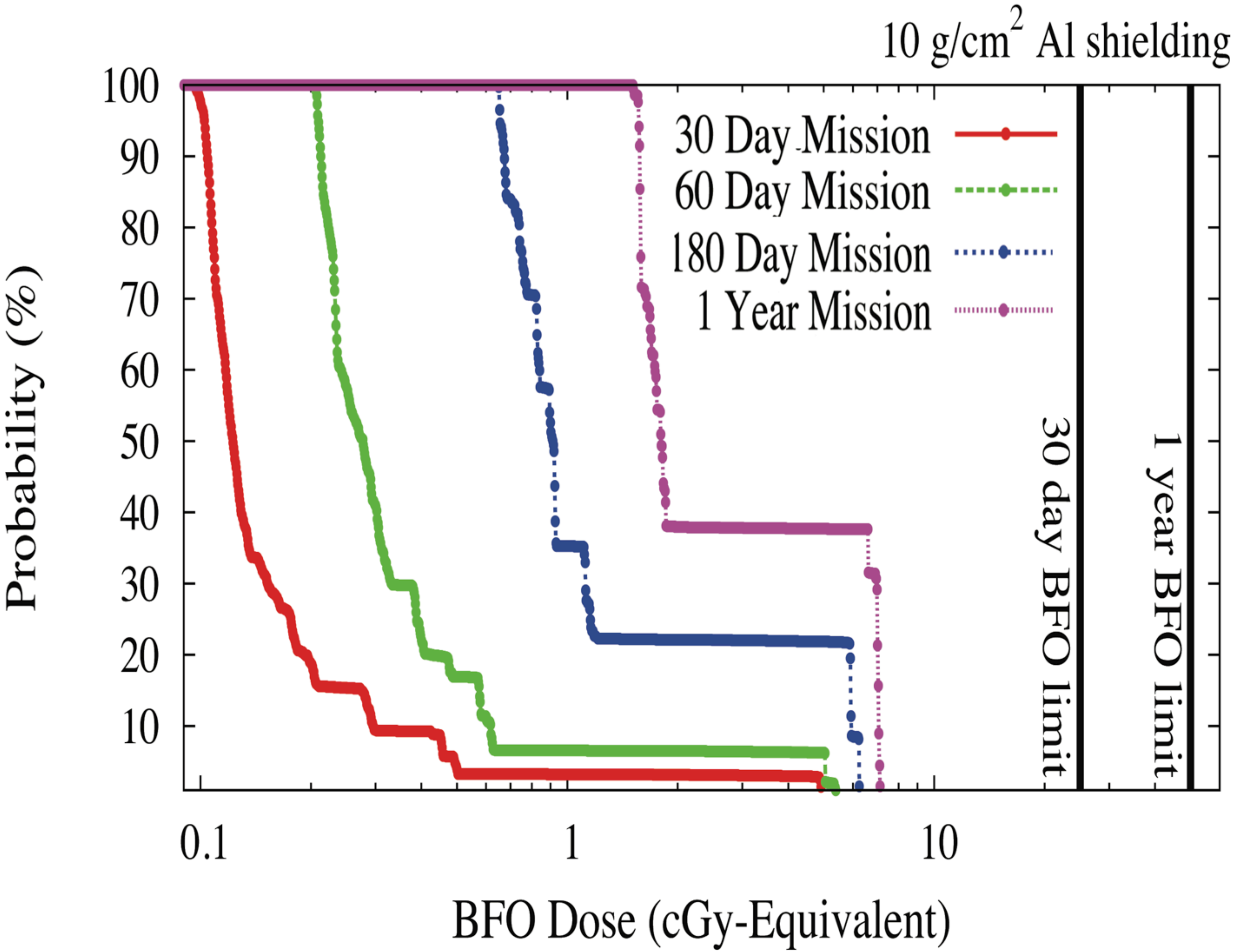
- Wilson, J, et al., **Localized Features in the Albedo Proton Map of the Moon,** LRO Special Issue of Icarus, 2015
- Schwadron et al., Signatures of Volatiles from Albedo Protons, LRO Special Issue of Icarus, 2015

Articles with Impact for Human Exploration

- Joyce et al., Analysis of the potential radiation hazard of the 23 1 July 2012 SEP event observed by STEREO A using 2 the EMMREM model and LRO/CRaTER, *Space Weather, In Press, 2015*
- Mazur et al., Update On Radiation Dose From Galactic and Solar Protons at the Moon Using the LRO/CRaTER Microdosimeter, *Space Weather, 2015*
- Winslow et al., Interplanetary Coronal Mass Ejections from MESSENGER orbital observations at Mercury, *JGR*, in press 2015
- de Wet, W.C.; Townsend, L.W.; Xu, G.; and Smith, W.J.: The Standalone Package for Enhanced Estimation of Dose Distribution. Nuclear Technology, December 2015 (in press).

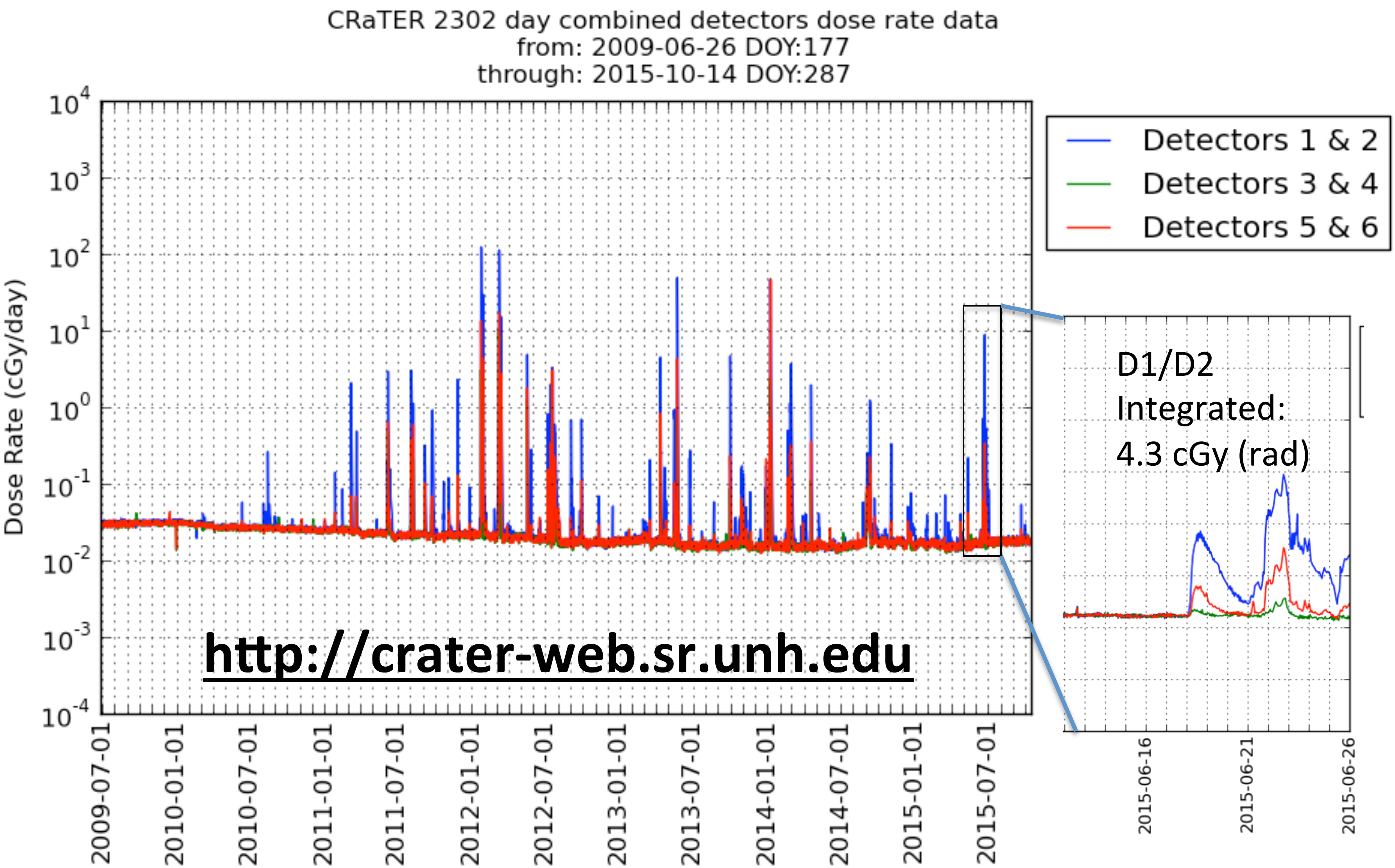


Prediction (Dalton)
Prediction (Gleissberg)
Cycle 23
Cycle 24
Lunar Surface Dose Rate (cGy/yr)
Sunspot Number
ACE
CRaTER
Sunspot Number
Model
Year

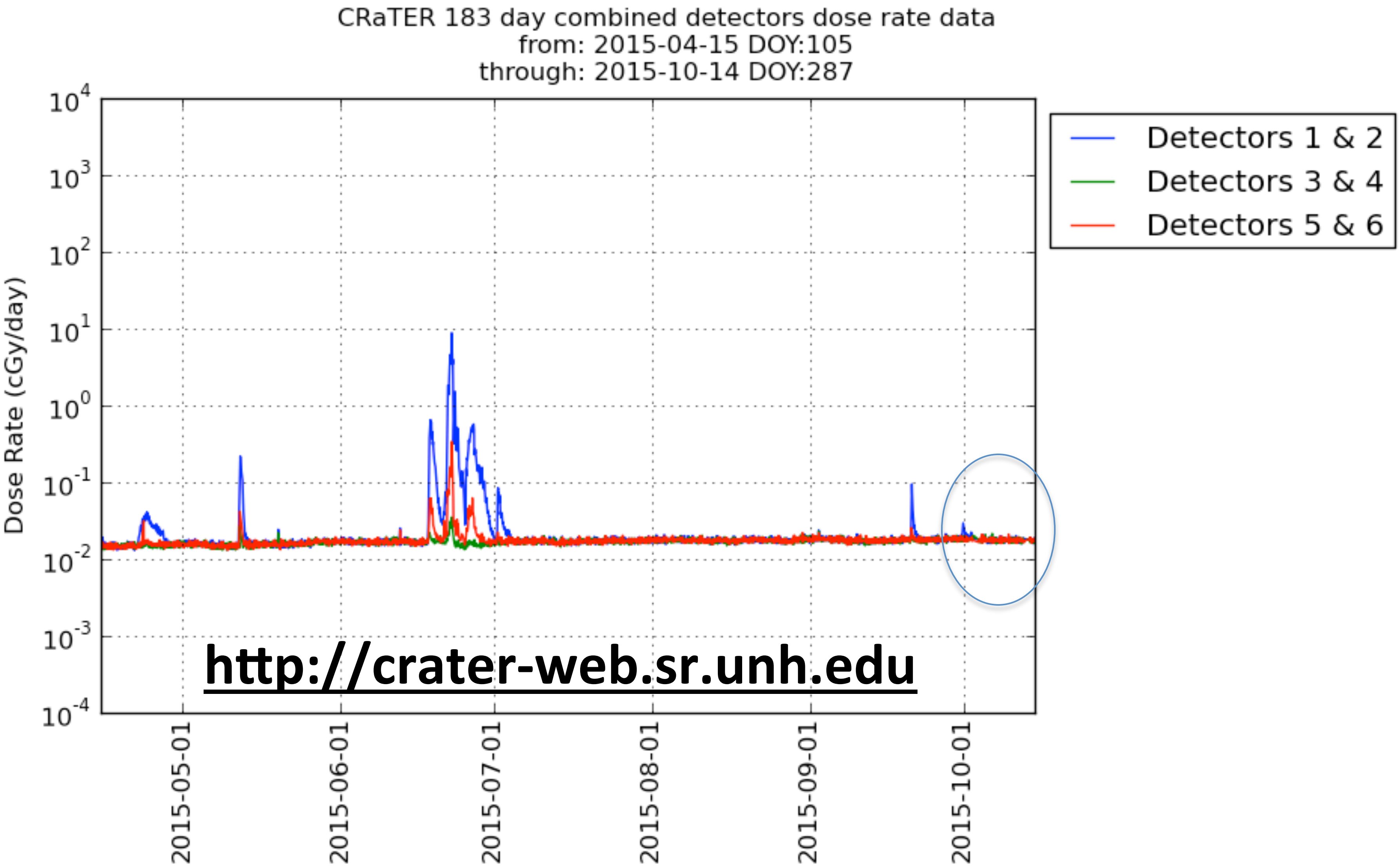


10 g/cm2 Al shielding
100
90
80
70
60
50
40
30
20
10
Probability (%)
30 Day Mission
60 Day Mission
180 Day Mission
1 Year Mission
30 day BFO limit
1 year BFO limit
0.1
1
10
BFO Dose (cGy-Equivalent)

Is Activity in Decline?!



Are there further surprises in store?



http://crater-web.sr.unh.edu